REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER	2. GOVT ACCESSION NO.
3. RECIPIENT'S CATALOG NUMBER	
4. TITLE (and Subtitle) MX Missile Basing and ABM Defenses	5. TYPE OF REPORT & PERIOD COVERED Final
	6. PERFORMING ORG. REPORT NUMBER IDA Paper P-1655
7. AUTHOR(s) Jerome Bracken	8. CONTRACT OR GRANT NUMBER(s) Central Research
9. PERFORMING ORGANIZATION NAME AND ADDRESS Institute for Defense Analyses Program Analysis Division 1801 N. Beauregard Street Alexandria, VA 22311	10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
11. CONTROLLING OFFICE NAME AND ADDRESS	12. REPORT DATE April 1982
	13. NUMBER OF PAGES 36
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)	15. SECURITY CLASS. (of this report) UNCLASSIFIED
	15a. DECLASSIFICATION/DOWNGRADING SCHEDULE n/a

16. DISTRIBUTION STATEMENT (of this Report)

This document is unclassified and suitable for public release.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

MX basing, antiballistic missile, ballistic missile defense, exoatmospheric interceptor, endoatmospheric interceptor, layered defense, impact-point prediction, deceptive basing, ICBM, ABM, BMD.

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Cost-effectiveness tradeoffs among missiles, silos or shelters, exoatmospheric interceptors and endoatmospheric interceptors are explored. Symmetric U.S. and Soviet force structures are treated, as well as U.S. options against Soviet force structures similar to the current one. The effects of exoatmospheric interceptor impact-point prediction are highlighted.

IDA PAPER P-1655

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PREFACE

This paper examines cost-effectiveness tradeoffs among land-based missiles, their silos or shelters, exoatmospheric interceptors and endoatmospheric interceptors. It treats a symmetric situation in which the U.S. and Soviets have identical forces, and an asymmetric situation in which the U.S. is designing a force on the basis of a Soviet force similar to the present one.

The research was motivated by the paper "Ballistic Missile Defense: A Potential Arms Control Initiative", LA-8632, Los Alamos National Laboratory, January 1981, which examines layered defense of MX missiles. The present paper uses the same model and data, exploring options not treated in the Los Alamos paper. The two topics emphasized here are: (1) sensitivities of results to impact-point prediction of exoatmospheric interceptors, and (2) tradeoffs among resources designed against a Soviet force similar to the present one.

CONTENTS

A. INTRODUCTION

This paper examines tradeoffs among land-based offensive missiles, their silos or shelters, and their exoatmospheric and/or endoatmospheric defensive missiles. These tradeoffs are of importance in two principal contexts. First, combinations of forces which yield a specified number of warheads[1] delivered in a second strike, after having absorbed a first strike, are of interest. Second, combinations of forces which allow a first strike while denying a successful retaliation are of interest. (From a deterrence point of view these combinations should be avoided, for they may encourage a first strike.) The paper explores a number of important sensitivities, particularly among defensive missile options.

Two situations are treated. The first situation is symmetric; both sides are assumed to have the same force structures, effectiveness parameters and costs. Combinations of both sides' forces yielding approximately 1,000 warheads delivered in the second strike are identified. The second situation is asymmetric; the U.S. assumed to be designing a force against a Soviet force similar to the present one. Combinations of U.S. forces yielding approximately 1,000 warheads delivered in the U.S. second strike are identified.

The paper does not treat U.S. and Soviet strategic bomber and submarine forces. If either U.S. or Soviet land-based missiles were vulnerable to the bomber- or submarine-delivered

[1]The term "warheads" is used throughout this paper; the term "re-entry vehicles" (or "RVs") can be substituted if the reader prefers to think in these terms.

weapons of the other side, the results of this paper would be less meaningful and an analysis of broader scope would be required.

The model and the effectiveness and cost parameters are drawn from a study published by the Los Alamos National Laboratory (Reference [1]). That study treats the symmetric case, several additional aspects of which are analyzed here. That study does not treat the asymmetric case explored in the present paper.

B. MODEL

1. Definitions and Values of Effectiveness Inputs

Definitions are given below. Inventories are varied in the analysis. Parameters and kill probabilities are fixed, and their values are given in brackets. Leakage factors are computed as an intermediate step. Outcomes are the final results of the computations.

Inventories

- M = missiles
- H = silos or shelters
- X = exoatmospheric interceptors
- N = endoatmospheric interceptors
- y = endoatmospheric interceptors per defended silo or shelter.

Parameters

- μ = warheads per missile [10]
- χ = kill vehicles per exoatmospheric interceptor [10]
- f = fraction of targets attacked in second strike that are protected by exoatmospheric interceptors [.6 or 1.0].

Kill Probabilities

- p = probability that warhead kills silo or shelter [.8]
- q = probability that exoatmospheric kill vehicle kills warhead [.8]

r = probability that endoatmospheric interceptor kills warhead [.7].

Leakage Factors

L_x = percent of warheads which are not killed by exoatmospheric interceptors defending missiles

L_n = percent of warheads which are not killed by endoatmospheric interceptors defending missiles

Λ_x = percent of warheads which are not killed by exoatmospheric interceptors defending value.

Outcomes

S = missiles surviving first strike

W = warheads delivered in second strike.

2. Attrition Equations

The model basically has three levels, as defenses are introduced. The equations are given below, followed by interpretations in subsequent pages.

Missiles in Silos or Shelters, No Defense (First Level)

$$S = M(1-p')^{\frac{\mu' M'}{H}}$$

$$W = \mu S.$$

Missiles in Silos or Shelters, Endoatmospheric Defense (Second Level)

$$L_n = (1-r)^{y / \frac{\mu' M'}{H}}$$

$$S = M(1-p' L_n)^{\frac{\mu' M'}{H}}$$

$$W = \mu S.$$

Missiles in Silos or Shelters, Exoatmospheric and Endoatmospheric Defense (Third Level)

$$L_x = (1-q)^{\chi X / \mu' M' (\frac{M}{H})}$$

$$L_n = (1-r)^{y/\frac{\mu'M'}{H}L_x}$$

$$S = M(1-p'L_nL_x)^{\frac{\mu'M'}{H}}$$

$$\Lambda_x' = (1-q')^{X'X'/\mu Sf'}$$

$$W = \mu S[f'\Lambda' + (1-f')].$$

3. Interpretation of Attrition Equations

Interpretation of the attrition equations of the model is relatively straightforward. In the first level, each silo or shelter is attacked by $\frac{\mu'M'}{H}$ warheads. Its probability of survival is $(1-p')^{\frac{\mu'M'}{H}}$. The expected number of survivors is $M(1-p')^{\frac{\mu'M'}{H}}$. The number of warheads delivered in the second strike is μS. This sequence assumes that attacking warheads are distributed identically over all of the silos or shelters, which maximizes the destruction by the warheads. A crucial assumption is that warheads are distributed over H rather than M; position location uncertainty (PLU) is preserved.

In the second level, each silo or shelter which holds missiles is defended by y endoatmospheric interceptors. The warheads directed at each such silo or shelter number $\frac{\mu'M'}{H}$; they are attacked by y interceptors, identically distributed over these warheads. The probability of survival of each warhead is $(1-r)^{y/\frac{\mu'M'}{H}}$, termed the leakage factor L_n of the endoatmospheric defense. The probability of a missile surviving leakage and kill is $(1-p'L_n)$ raised to the number of attacking warheads $\frac{\mu'M'}{H}$. The expected number of survivors and warheads delivered on the second strike are computed as in the first level.

A key assumption is that endoatmospheric interceptors can protect the silos or shelters which hold missiles by knowing where the incoming warheads are headed. It should be possible to distinguish warheads from decoys, since decoys are lighter than warheads (otherwise the attacker should replace the decoys by warheads). Furthermore, since there is little possiblity of the warhead maneuvering in the final part of its incoming trajectory, the assumption of knowledge of its destination by the defense is reasonable. Another key assumption is that the interceptors themselves are not in known locations; thus they cannot be targeted by early-arriving warheads. Or, if their possible locations are known, the assumption is made that they have been deployed in such a way that the attacker chooses not to attack them. This might be accomplished by moving interceptors among launch locations in an analogous manner to moving missiles among silos. If, alternatively, the endoatmospheric interceptors were in some of the silos or shelters, they would need to defend themselves as the attack progressed, and extra interceptors would need to be provided for this function. Similar assumptions are implied about the interceptor radars, which are not explicitly treated in this analysis.

In the third level, the first defense is by the exoatmospheric interceptors. Defending kill vehicles in number χX attack warheads directed at missiles in number $\mu' M'(\frac{M}{H})$, identically distributed over these warheads. The probability of survival of each warhead is $(1-q)^{\chi X/\mu' M'(\frac{H}{M})}$, termed the leakage factor L_x of the exoatmospheric defense. By a logic identical to that of the second level discussed above, the probability of a missile surviving exoatmospheric and endoatmospheric leakage and kill is $(1-p'L_nL_x)$ raised to the number of attacking warheads per silo or shelter $\frac{\mu' M'}{H}$. The number of surviving missiles S is computed as previously.

However, in this case there is a very significant additional process if the other side also possesses exoatmospheric interceptors. A portion f' of the surviving warheads μS, presumably directed at value targets on the second strike, is confronted by defending exoatmospheric kill vehicles in number $\chi'X'$. The leakage Λ_X' through the defended portion f' is $(1-q')^{\chi'X'/\mu Sf'}$. The fraction of the warheads delivered is thus $f'\Lambda_X' + (1-f')$.

The critical assumption in this third level is that the exoatmospheric defense can perform impact-point prediction, identifying those warheads which are directed at silos or shelters containing missiles. This enables the kill vehicles of the defense to efficiently attack $\frac{M}{H}$ of the warheads. In addition to performing impact-point prediction, the defense must sort out other objects and decoys above the atmosphere where the other objects have not burned up. Deployment of maneuvering warheads can frustrate impact-point prediction, for the maneuvering can take place after the exoatmospheric defense. The present analysis will highlight quantitatively the effect of impact-point prediction on results.

Many of the physical factors bearing on all three levels of the model are discussed in the recent MX missile basing study performed by the Office of Technology Assessment (Reference [3]). Note that the model does not deal with damage to recources for command, control and communications necessary to launch a second strike.

Finally, note that when computing expression of the form $(1-p)^a$, when a is not integer, it is important to replace this expression by $(1-p)^{[a]}(1-\langle a\rangle p)$, where $[a]$ is the integer part of a and $\langle a\rangle$ is the non-integer part of a. This ensures, for example, that if there are 100 targets and 240 attackers, 40 targets receive 3 attackers each and 60 targets receive 2 attackers each, rather than 100 targets receiving 2.4 attackers each. (The computer program implementing the model generates results both ways; there are often significant differences in results.)

4. Costs

Costs are taken from the Los Alamos study. They are as follows:

	Development Cost ($ Millions)	Production Cost ($ Millions)
Missiles (M)	8,000	$60\ (M+X)^{.78}$
Exoatmospheric Interceptors (X)	7,000	
Endoatmospheric Interceptors (N)	5,000	$16\ N^{.78}$
Silos (H)	0	6 H
Shelters (H)	5,000	3 H

To illustrate how these costs match force structures, the following information is of interest:

		Total Cost ($ Millions)	Average Cost ($ Millions)	Marginal Cost ($ Millions)
Missiles (M)[2]	100	10,178	102	17
	200	11,741	59	15
	400	14,423	36	13
Exoatmospheric Interceptors (X)[2]	100	8,391	84	14
	200	9,683	48	13
Endoatmospheric Interceptors (N)	200	5,998	30	3.9
	400	6,713	17	3.4
	800	7,941	9.9	2.8
Silos (H)	1,000	6,000	6	6
	2,000	12,000	6	6
	3,000	18,000	6	6
	4,000	24,000	6	6
Shelters (H)	1,000	8,000	8	3
	2,000	11,000	5.5	3
	3,000	14,000	4.67	3
	4,000	17,000	4.25	3

[2] Cost of missiles assumes no exoatmospheric interceptors. Cost of exoatmospheric missiles assumes 200 missiles.

Missiles and exoatmospheric interceptors are assumed to share many common features and thus have common production learning curve effects. Endoatmospheric interceptors are assumed to have separate production learning curve effects.

The present paper treats silos almost exclusively. Several results are given for shelters, but the costs displayed are almost always for silos. As can be seen from the table above, shelters are much less expensive beyond 2,000. The probability of kill of a warhead against a silo or a shelter is assumed to be .8. Presumably, silos would be harder than shelters and thus the probability of kill against a missile in a silo should be less than against a shelter. The present paper should not be considered to distinguish between silos and shelters; more analysis is necessary.

C. SYMMETRIC ANALYSIS

1. Previous Results, With Some Modifications

The Los Alamos study presents symmetric force structures which are stated to be minimum-cost inventories needed on both sides to achieve the specified deterrence criterion of 1,000 warheads delivered on the second strike. These force structures and their associated warheads delivered, costs, and warheads delivered per unit cost are as follows:

Missiles M	Silos or Shelters H	Exos X	Endos N	Endos per Defended Silo or Shelter y	Warheads Delivered W	Cost ($ Billions) C	Warheads Delivered per $ Billion W/C
Case 1: Missiles in shelters							
150	3,450 shelters	0	0	0	978	26.3	37.1
Case 2: Missiles in shelters defended by endos							
115	1,610 shelters	0	230	1	1,008	26.4	38.2

Missiles M	Silos or Shelters H	Exos X	Endos N	Endos per Defended Silo or Shelter y	Warheads Delivered W	Cost ($ Billions) C	Warheads Delivered per $ Billion W/C
Case 3: Missiles in silos defended by exos and endos, f=0.6							
220	420 silos	200	420	1	1,003	31.0	32.4
Case 4: Missiles in silos defended by exos and endos, f=1.0							
300	500 silos	200	1,000	2	1,085	34.1	31.8

Several modifications to and comments about the above results are of interest:

(1) Case 2 assumes that half of the 230 endos protect themselves, giving an effective number of 115 endos protecting missiles. Raising the effective number of endos from 115 to 230 by eliminating the requirement for this self-protection would raise warheads delivered from 1,008 to 1,124. If this were assumed costless, W/C would be 42.6. Alternatively, if 230 more endos were provided for self-defense, for a total of 460 endos, the total cost would be $27.2 Billion and W/C would be 41.3. Both modifications would significantly raise W/C.

(2) Cases 3 and 4 assume that endos defend all silos. But if endos were provided for missiles only, on the theory that exos would be fired before endos and thus would need no defense, costs would decrease by $.7 Billion and $1.1 Billion, respectively. The values of W/C would increase from 32.4 to 33.1 and from 31.8 to 32.9, respectively.

(3) The above options are not necessarily minimum-cost combinations. The algorithm used to obtain the above results apparently converges to a local minimum which is not the global minimum. For instance, in Case 4 (f=1.0) an option resulting in more warheads delivered at lower cost is M = 270, H = 445, X = 175, N = 1335, y = 3, which yields

W = 1175 and C = 34.0. James E. Falk identifies a number of properties of the nonconvex cost minimization problem in Reference [2].

(4) It should be noted that the cost of the force structure of Case 2 (the option with all endos) is lower than that of Cases 3 and 4 (the overlay options). Furthermore, adding more endos can lead to far more cost-effective force structures, as will be explored below.

2. Silos and Endoatmospheric Interceptors

Figure 1 presents, for 200 missiles, warheads delivered in the second strike as a function of cost for 500 silos, 1,000 silos, 1,500 silos and 2,000 silos. (The partial curve for 1,500 silos is shown because it results in more than 1,000 surviving warheads with only 200 endos.) The number of endos, and the cost-effectiveness measure W/C, are shown along each curve. It is possible to generate very large numbers of surviving warheads, towards the upper limit of 2,000, by adding endos. At a certain point warheads delivered per unit cost decreases (see the upper ends of the curves for 1,000 silos and 2,000 silos.)

Figure 1 shows that warheads delivered as a function of cost is most favorable with fewer silos and many endos. However, the upper limit on number of endo shots per defended silo is a technologically uncertain parameter.[3] Therefore, if 1,000 surviving warheads are desired and the number of endo shots per defended silo is constraining, silos can be substituted for endos.

Note that for 2,000 silos, 100 endos ensures almost 1,000 warheads delivered on the second strike. The ABM Treaty limits interceptors to 100 and radars to 18. Thus, if there were

[3] See, for example, Chapter 3 of Reference [3].

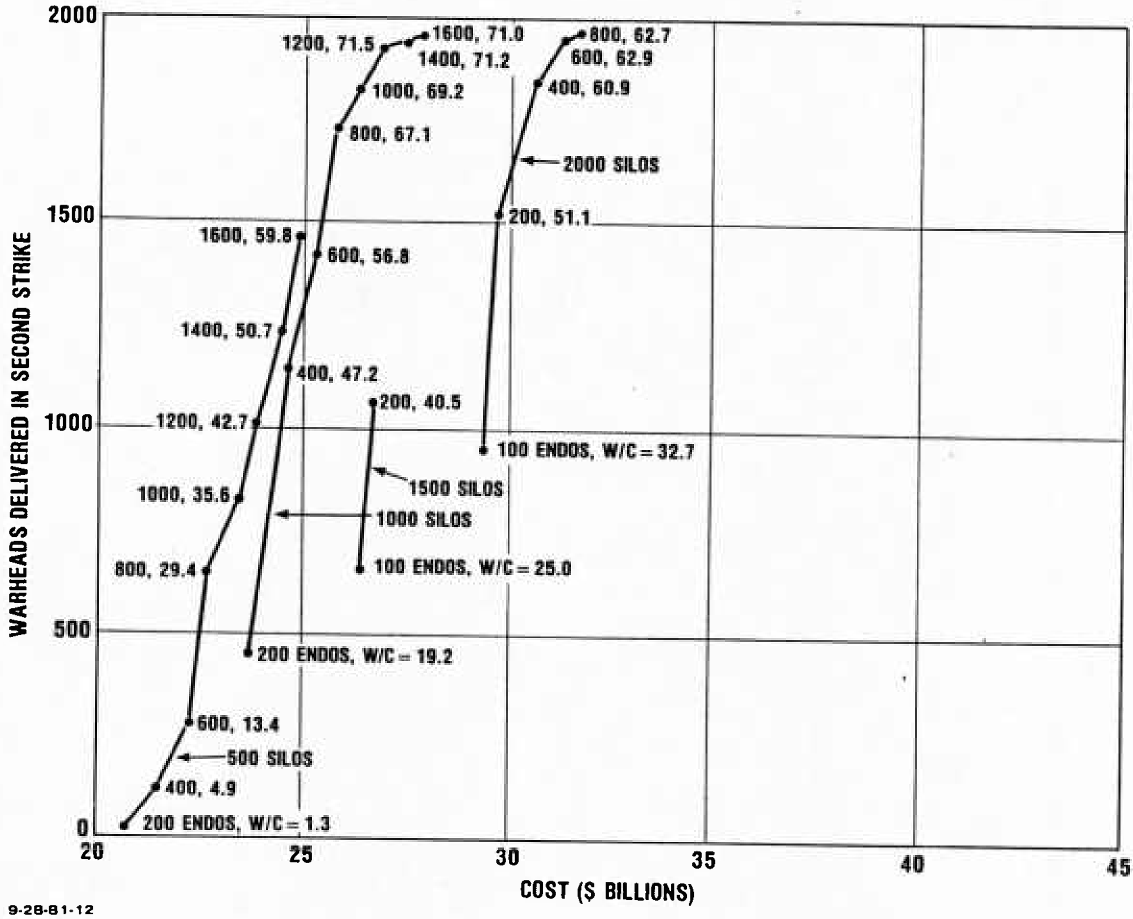


Figure 1. WARHEADS DELIVERED AS A FUNCTION OF COST FOR 200 MISSILES, WITH SHELTERS AND ENDOS VARIED

2,000 silos organized into 18 groups of 111 silos, with each group of 111 silos including 11 missiles and either 6 or 5 interceptors, almost 1,000 warheads could be delivered on the second strike.

Recall that silos and shelters are essentially treated interchangeably here. Costs shown are for silos; thus the term silos is used.

3. Silos and Exoatmospheric Interceptors

Figure 2 superimposes results for several options including exoatmospheric interceptors onto Figure 1. The exo options generally are less cost-effective than the better endo options.

A_1 and A_2 correspond to Case 3 above, with and without impact-point prediction. B_1 and B_2 correspond to Case 4 above, with and without impact-point prediction.

C_1, C_2 and C_3 are results for 1,000 silos and 100 exos. C_1 assumes impact-point prediction and is attained for both f=.6 and f=1.0, while C_2 and C_3 assume no impact-point prediction and are attained for f=.6 and f=1.0, respectively.

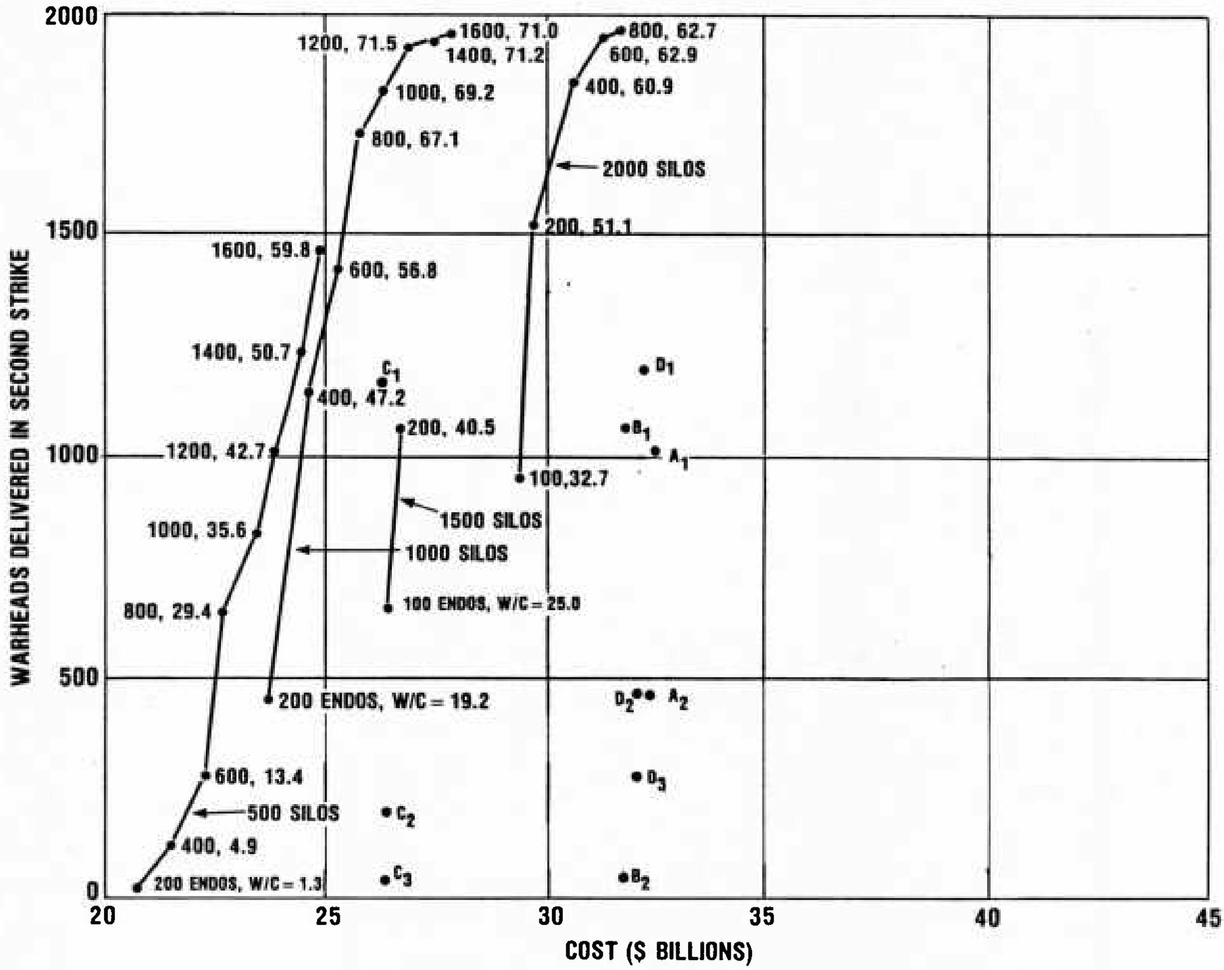
D_1, D_2 and D_3 are parallel results for 2,000 silos and 100 exos. Note that cost-effectiveness decreases from C_1 to D_1.

In all of these cases, when there is not exo impact-point prediction, results are seriously affected. Impact-point prediction will be discussed in more detail below.

4. Exo Impact-Point Prediction Sensitivity Analyses

Table 1 displays warheads surviving the first strike and missiles delivered in the second strike (through the exoatmospheric defenses possessed by the first striker), with impact-point prediction and without impact-point prediction.

The first two lines correspond to Cases 3 and 4 presented above. In Case 3, if there is impact-point prediction, 215 of



A_1 CASE 3 SOLUTION, IMPACT-POINT PREDICTION, W/C = 32.4
A_2 CASE 3 SOLUTION, NO IMPACT-POINT PREDICTION, W/C = 15.7

B_1 CASE 4 SOLUTION, IMPACT-POINT PREDICTION, W/C = 31.8
B_2 CASE 4 SOLUTION, NO IMPACT-POINT PREDICTION, W/C = 0.8

C_1 1000 SILOS, 100 EXOS, f = 0.6 OR f = 1.0, IMPACT-POINT PREDICTION, W/C = 43.0
C_2 1000 SILOS, 100 EXOS, f = 0.6, NO IMPACT-POINT PREDICTION, W/C = 24.1
C_3 1000 SILOS, 100 EXOS, f = 1.0, NO IMPACT-POINT PREDICTION, W/C = 1.3

D_1 2000 SILOS, 100 EXOS, f = 0.6 OR f = 1.0, IMPACT-POINT PREDICTION, W/C = 37.3
D_2 2000 SILOS, 100 EXOS, f = 0.6, NO IMPACT-POINT PREDICTION, W/C = 15.0
D_3 2000 SILOS, 100 EXOS, f = 1.0, NO IMPACT-POINT PREDICTION, W/C = 7.5

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Figure 2. WARHEADS DELIVERED AS A FUNCTION OF COST FOR 200 MISSILES, WITH SHELTERS AND ENDOS VARIED: VARIOUS OPTIONS WITH EXOS ALSO SHOWN

220 missiles survive the first strike. These missiles fire 2,150 warheads, of which 40 percent, or 860, get through without confronting the opposing exos. The other 1,290 are met by 2,000 kill vehicles and 143 get through, for a total of 1,003. If there is no impact-point prediction, 119 of 200 missiles survive the first strike. These missiles fire 1,190 warheads of which 40 percent, or 476, get through without confronting the opposing exos. The other 714 are met by 2,000 kill vehicles and 9 get through, for a total of 485.

Table 1. EFFECT OF NOT HAVING IMPACT-POINT PREDICTION; 500 SHELTERS, EXOS AND ENDOS VARIED

Missiles M	Silos H	Exos X	Endos N	Missiles Surviving First Strike, Warheads Delivered in Second Strike: Impact-Point Prediction	No Impact-Point Prediction
		f=.6			
220	420	200	220	215, 1003	119, 485
		f=1.0			
300	500	200	600	268, 1085	87, 26
		f=.6			
200	500	100	200	182, 1020	38, 152
200	500	100	400	197, 1175	82, 347
200	500	100	600	200, 1196	121, 583
200	500	200	200	200, 912	170, 728
200	500	200	400	200, 912	193, 867
200	500	200	600	200, 912	198, 902
		f=1.0			
200	500	100	200	182, 1020	38, 7
200	500	100	400	197, 1175	82, 135
200	500	100	600	200, 1196	121, 406
200	500	200	200	200, 400	170, 293
200	500	200	400	200, 400	193, 373
200	500	200	600	200, 400	198, 394

Not having impact-point prediction has a dramatic effect in Case 4. Of 300 missiles, 87 remain after the first strike. Their 870 warheads are confronted by 3,000 kill vehicles, and only 26 survive.

The rest of the table is also interesting. Note that when both sides have 200 exos, with impact-point prediction, changing f from .6 to 1.0 always results in changing warheads delivered from 912 to 400 because, although 200 defensive exos provide 200 surviving missiles, the retaliation is limited to 400 delivered warheads due to the first striker's exos protecting all of the first striker's value.

For the small number of exos, namely 100, the effect of no impact-point prediction is severe. Consider the first line under f=1.0. With no impact-point prediction surviving missiles are reduced from 182 to 38. The 380 warheads are met by 1,000 kill vehicles, so only 7 get through. This effect is similar to that of Case 4, but here only 100 exos on both sides are enough to cause it.

Table 2 displays the same type of information as Table 1, showing how adding silos yields warheads delivered in the second strike when there are 100 exos with no impact-point prediction. Recall, however, that if 200 rather than 100 exos were included there would be at most 912 warheads delivered in the second strike when f=.6 and 400 when f=1.0 because of the first striker's exos, independent of the number of silos.

Table 3 displays the same type of information as Tables 1 and 2 showing the effects of mixes of silos and exos, in this case with no endos. With impact-point prediction, for both f=.6 and f=1.0, warheads delivered decrease as exos increase for all cases except f=.6 and 500 silos. With no impact-point prediction, f=1.0, and 1,000 or 2,000 silos, note that warheads delivered increase between 100 and 200 exos and decrease between 200 and 300 exos.

Table 2. EFFECT OF NOT HAVING IMPACT-POINT PREDICTION; 100 EXOS and 200 ENDOS, SHELTERS VARIED

Missiles M	Silos H	Exos X	Endos N	Missiles Surviving First Strike, Warheads Delivered in Second Strike: Impact-Point Prediction	No Impact-Point Prediction
	f=.6				
200	300	100	200	34, 134	7, 29
200	500	100	200	182, 1020	38, 152
200	1000	100	200	200, 1200	128, 628
200	2000	100	200	200, 1200	185, 1046
	f=1.0				
200	300	100	200	34, 3	7, 0
200	500	100	200	182, 1020	38, 75
200	1000	100	200	200, 1200	128, 480
200	2000	100	200	200, 1200	185, 1046

Table 3. EFFECT OF NOT HAVING IMPACT-POINT PREDICTION; SHELTERS AND EXOS VARIED

Missiles M	Silos H	Exos X	Missiles Surviving First Strike, Warheads Delivered in Second Strike: Impact-Point Prediction	No Impact-Point Prediction
	f=.6			
200	500	100	116, 552	15, 58
200	500	200	185, 820	100, 402
200	500	300	198, 820	134, 537
200	1000	100	192, 1124	54, 219
200	1000	200	200, 911	141, 588
200	1000	300	200, 829	163, 661
200	2000	100	200, 1199	104, 481
200	2000	200	200, 912	168, 715
200.	2000	300	200, 829	181, 740
	f=1.0			
200	500	100	116, 356	15, 0
200	500	200	185, 346	100, 40
200	500	300	198, 233	134, 43
200	1000	100	192, 1124	54, 35
200	1000	200	200, 400	141, 188
200	1000	300	200, 240	163, 108
200	2000	100	200, 1200	104, 240
200	2000	200	200, 400	168, 285
200	2000	300	200, 240	181, 171

In summary, Tables 1, 2 and 3 show that having exos without impact-point prediction often results in serious to total degradation of second strike capability due to second striker's missiles not surviving. Furthermore, Tables 1, 2 and 3 show that large numbers of exos in a symmetric force structure, particularly with a complete coverage of value, sharply reduce warheads delivered in the second strike.

D. ASYMMETRIC ANALYSIS

Results of the symmetric analysis presented above are of principal interest in the context of arms-control agreements involving identical forces. Requirements for 1,000 warheads delivered on the second strike can be satisfied by force structures of 200 missiles with various combinations of silos and endos at various costs.

Current inventories of missiles and warheads, however, are larger than those analyzed in the symmetric case. And a deceptive basing posture on one side but not the other may lead to different first and second strike characteristics than observed in the symmetric analysis.

The asymmetric analysis which follows deals with a presumptive Soviet force of 1,300 missiles with an average of 5 warheads per missile. A U.S. force is to be designed which survives a first strike by this Soviet force and retaliates with roughly 1,000 warheads. Each U.S. missile is assumed to have 10 warheads.

1. <u>200 Missiles in 2,000 Silos</u>

The first U.S. force explored has 200 missiles in 2,000 silos. Figure 3 shows U.S. warheads delivered as a function of cost for three cases: (1) no U.S. exos, and endos varied from 0 to 2,000; (2) 50 U.S. exos with impact-point prediction, and endos varied from 0 to 2,000; (3) 50 U.S. exos with no impact-point prediction, and endos varied from 0 to 2,000.

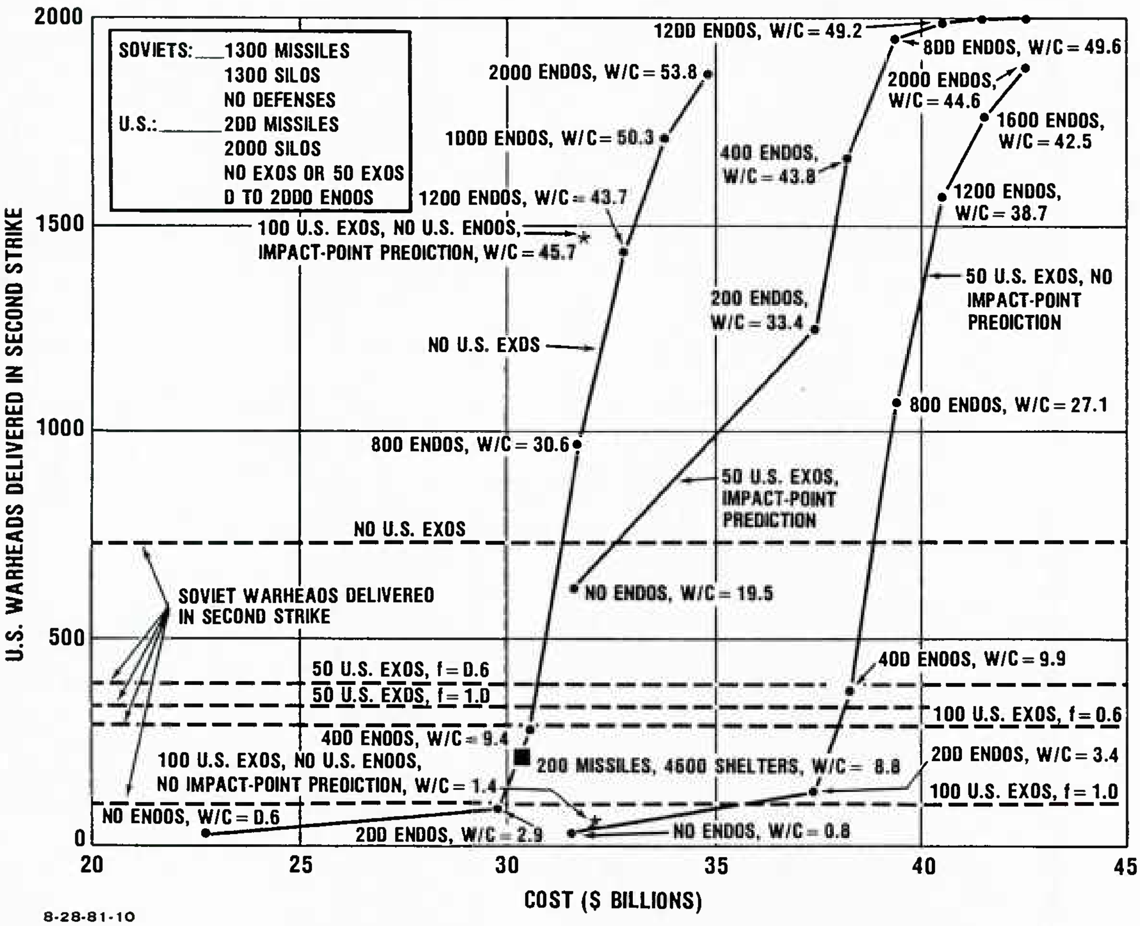

Figure 3. U.S. WARHEADS DELIVERED AS A FUNCTION OF COST

Also displayed in Figure 3, denoted by a square, is the result with the originally proposed MX/Multiple Protective Shelters basing scheme, namely 200 missiles, 4,600 shelters, and no defenses. Warheads delivered on the second strike number 268 for a cost of $30.5 Billion (W/C = 8.8).

Figure 3 also shows results of the U.S. deploying 100 exos and no endos, denoted by asterisks. With impact-point prediction, 1,468 U.S. warheads delivered are provided for $32.1 Billion (W/C = 45.7); without impact-point prediction, 44 U.S. warheads delivered are provided for the same cost (W/C = 1.4).

The dashed lines in Figure 3 illustrate the effects of U.S. exos on the Soviet second strike. With no U.S. exos the Soviets can absorb a first strike of 2,000 warheads on their 1,300 silos and respond with 740 warheads. With 50 U.S. exos, if the U.S. strikes first and f=.6, Soviet warheads delivered are reduced to 376; if f=1.0 Soviet warheads delivered are reduced to 340. With 100 exos, if the U.S. strikes first and f=.6, Soviet warheads delivered are reduced to 310; if f=1.0 Soviet warheads delivered are reduced to 106.

The option of 100 U.S. exos thus has widely varying outcomes. If impact-point prediction fails, warheads delivered go from 1,468 to 44. While the Soviet second strike capability of 740 warheads delivered when the U.S. is defended by endos may provide some stability, the U.S. defense of 100 exos with f=1.0 yielding 106 warheads delivered in the second strike seems to remove this stability. With 100 exos, the U.S. could direct some weapons to counterforce attack and other weapons to countervalue attack and ensure a smaller Soviet countervalue response. (For instance, if the U.S. were to allocate 1,500 warheads counterforce and 500 countervalue, the Soviets could deliver 340 surviving warheads countervalue.)

2. Varying Missiles and Silos

Figure 4 displays results for 200 and 400 missiles in 1,000, 2,000 and 3,000 silos. Cost and W/C are noted on the curves.

First consider the two middle curves. For 2,000 silos, approximately 1,000 surviving warheads are provided if the U.S. has approximately 1,000 endos. The curve for 200 missiles and 2,000 silos corresponds to the curve with no exos in Figure 3. Placing 400 missiles in 2,000 silos yields less warheads delivered to the breakpoint of about 1,400 endos because of the defensive allocation of defending all missiles equally. For example, if the Soviets target 6,500 warheads at 2,000 silos, or 3.25 each, and the U.S. has 800 endos, then 200 silos each defended by 4 endos yield more surviving missiles than 400 silos each defended by 2 endos. A better defense doctrine would be to defend some of the silos and leave others undefended, and thus the curve for 400 missiles can always be made to lie on or above the curve for 200 missiles. This paper does not consider the best endo defense doctrines; however, results do indicate that the doctrine becomes more important as missiles increase and silos decrease (see the case of 1,000 silos discussed below).

Now consider the two top curves, for 3,000 silos. (Note that there is a breakpoint at approximately 500 endos, and changing defense doctrine would bring the bottom curve up). With 400 endos and 3,000 silos the U.S. can achieve 1,000 warheads delivered, while about 1,000 endos are required with 2,000 silos. If the technical judgment is made that four or five shots per defended silo are too many, then 200 missiles in 3,000 silos defended by 400 endos (two shots per defended silo) provides 1,000 U.S. warheads delivered. The options with 3,000 silos cost more than those with 2,000 silos.

The dashed lines display Soviet warheads delivered in the second strike after a 200-missile attack and after a 400-missile attack. As in Figure 3, the former case yields 740 Soviet

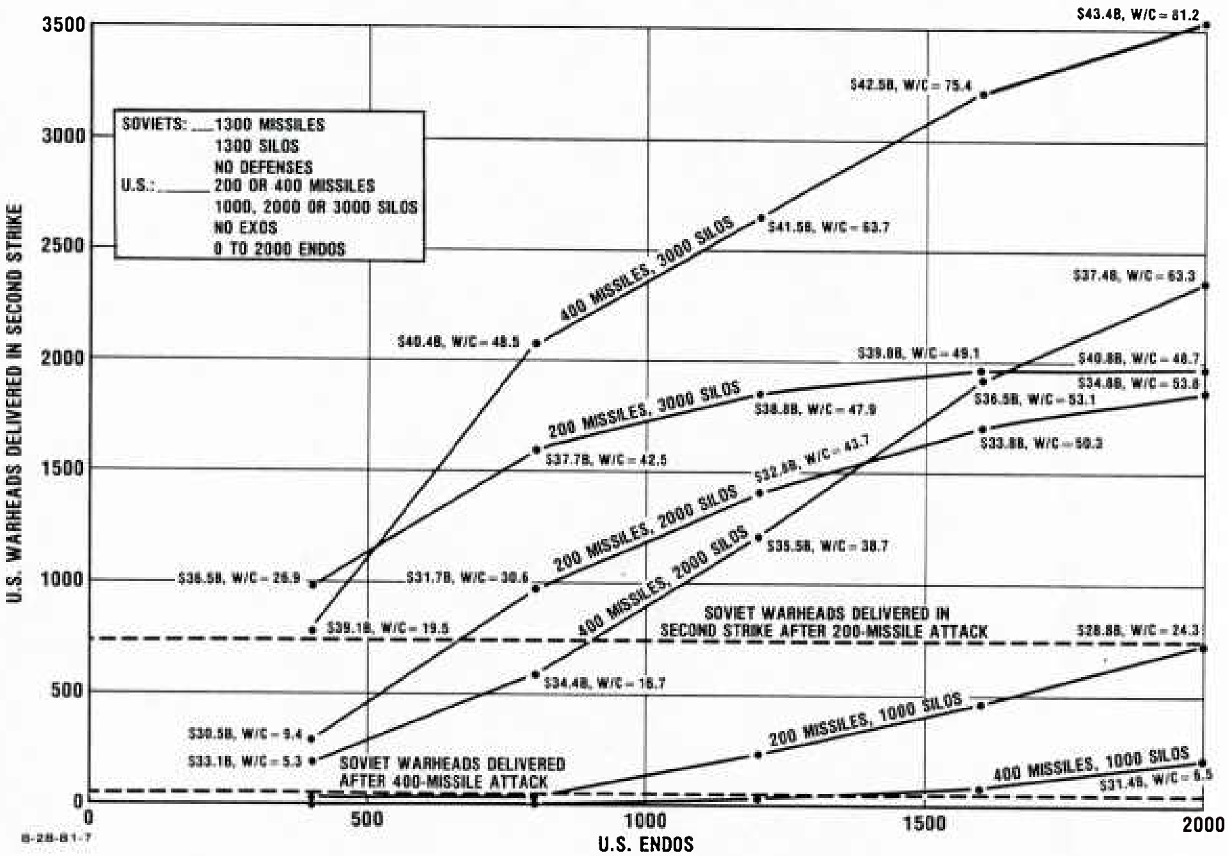

Figure 4. U.S. WARHEADS DELIVERED AS A FUNCTION OF U.S. ENDOS FOR SEVERAL MISSILE AND SILO COMBINATIONS

warheads delivered. However, after receiving an attack by 400 missiles, only 49 warheads are delivered on the second strike (even though no U.S. exo defense is present). This is because 4,000 warheads aimed at 1,300 silos reduce warheads from 6,500 to 49.

Now consider the two bottom curves, for 1,000 silos. When the silos are each targeted by 6.5 Soviet warheads, 800 or 1,200 defending U.S. endos do not ensure many warheads delivered. Even 2,000 endos, or 10 endos per defended missile, do not ensure 1,000 warheads delivered. Of course, defending a subset of missiles could bring the curve for 400 missiles above that for 200 missiles, or bring the curve for 200 missiles higher than the proportional allocation. However, the principal point is that 1,000 silos do not yield in the neighborhood of 1,000 warheads delivered except for very high numbers of endos per defended missile, which may not be technically feasible in the nuclear environment.

From a modeling point of view, more analysis is needed of the endo defense doctrine, with particular emphasis on allocations and on assessments with integers.

3. Overall Effects of Exo Impact-Point Prediction

Figure 5 shows the overall characteristics of exo defense with and without impact-point prediction. There are 2,000 silos. The solid curves represent impact-point prediction. The dashed curves represent no impact-point prediction.

The top two curves for 100 exos show that U.S. warheads delivered rise quickly as endos are added to 100 exos. For 200 U.S. missiles, 2,000 is the upper limit and is attained with 200 endos. For 400 U.S. missiles, 4,000 is the upper limit and is approached more gradually. The same cross-over behavior as discussed previously, which could be eliminated by changing defense doctrine, is present.

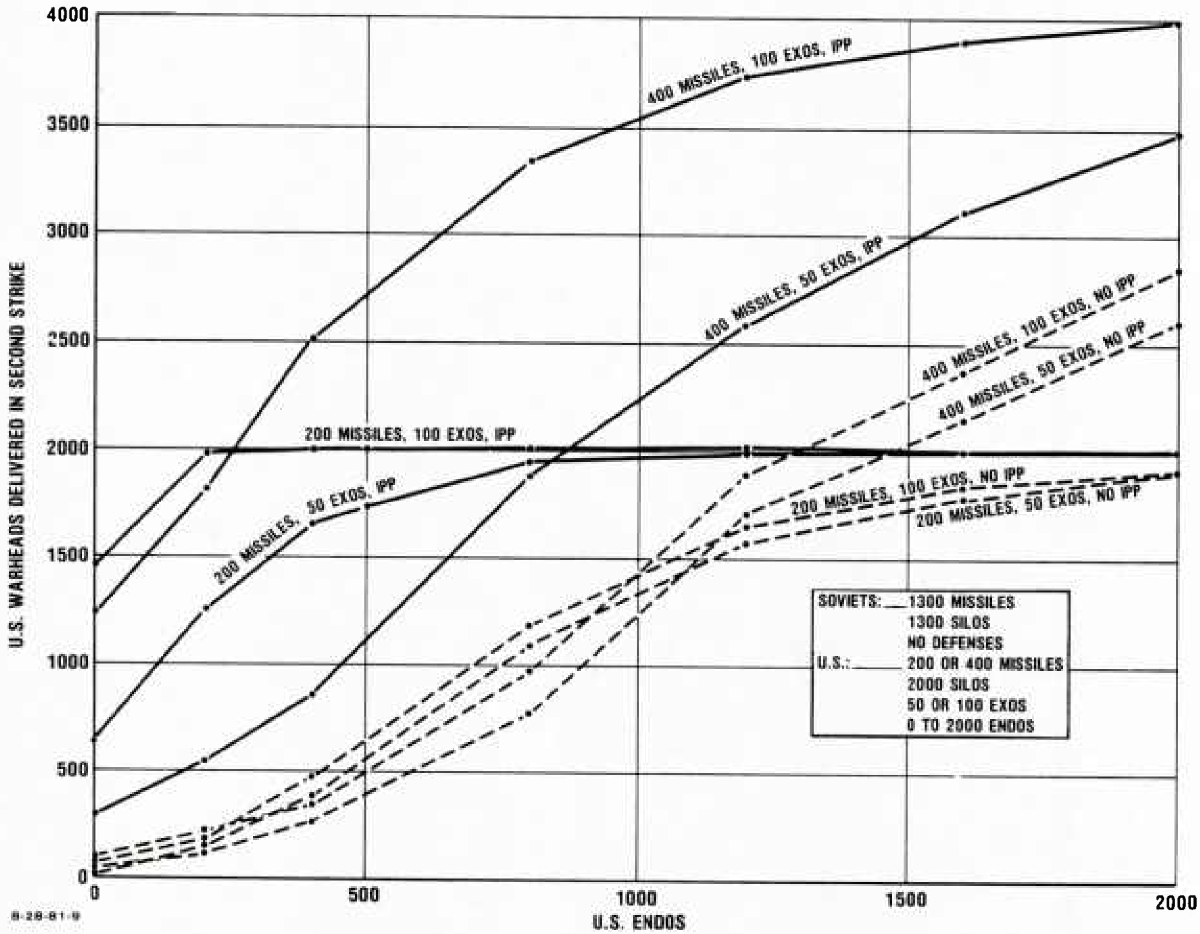

Figure 5. U.S. WARHEADS DELIVERED AS A FUNCTION OF U.S. ENDOS WITH AND WITHOUT EXO IMPACT-POINT PREDICTION

Overall, Figure 5 shows that, without impact-point prediction, for all cases the U.S. must have about 800 endos with 2,000 silos before the goal of 1,000 warheads delivered on the second strike is achieved. This result is also true, however, without any exos. Thus, from a qualitative point of view, exos add little effectiveness if they do not have impact-point prediction.

4. Two-Sided Analysis

The final analysis addresses the issue of identifying equal-size endo deployments which would allow both sides to have approximately the same second-strike capability, while allowing the Soviets to retain 1,300 missiles in 1,300 silos and U.S. adoption of a multiple-aimpoint deployment.

Figure 6 shows Soviet and U.S. warheads delivered in a second strike. The curves are for 200, 300 and 400 U.S. missiles. The desired symmetric outcome is about 1,000 missiles delivered on the second strike. The closest point shown is for 280 U.S. missiles, with 900 endos on both sides. This gives the U.S. a second strike capability of about 1,125 and the Soviets a second strike capability of about 850. Fewer U.S. missiles would yield a more equal second strike capability.

If a smaller symmetric second strike capability is desired, note that the 300 U.S. missile curve crosses the line of equal number of delivered warheads at about 500 warheads delivered. Both sides would have approximately 600 endos at this point. If 500 warheads delivered on the second strike is a sufficient deterrent, then an agreed deployment of 600 endos would guarantee the U.S. and Soviets this result.

E. LIMITATIONS AND DIRECTIONS FOR FURTHER WORK

The analysis of this paper does not consider exhaustion attacks. In particular, if the first striker knows how many

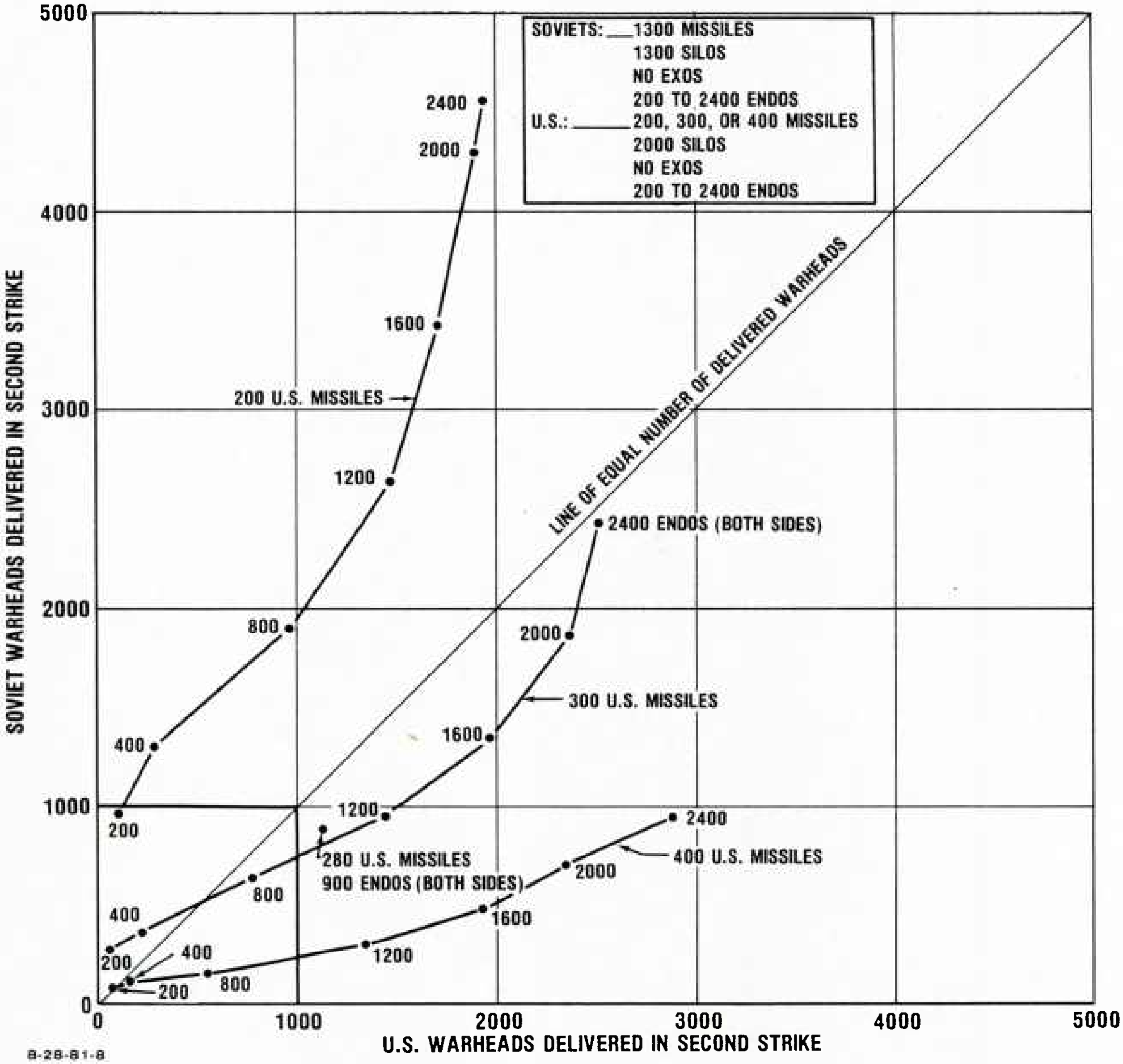

Figure 6. WARHEADS DELIVERED IN SECOND STRIKE: TWO-SIDED SOLUTION

endos are defending each missile, he can attack a subset of the missiles with sufficient warheads to exhaust the defense. Leakage and exhaustion attacks are explored in a recent study by Raymond E. Starsman (Reference [4]). The analysis of the present paper could be extended to compute results for both attack allocations and choose the better allocation.

Leakage attacks can be directed at a subset of the silos, and exo and endo defenses can cover a subset of the attacked silos (the latter is discussed in connection with Figure 4 above). A more complete analysis would take such options into account.

Independent of the allocations of both sides, the Los Alamos attrition model applied in this paper could be improved by treating distributions of warheads surviving exo and endo defenses and missiles surviving attacks by those warheads.

F. CONCLUDING REMARKS

In both the symmetric and asymmetric analyses of this paper, combinations of missiles, silos and endos achieve 1,000 warheads delivered at lower cost than do combinations which include exos. Furthermore, if exos do not have impact-point prediction they are not cost-effective; and, exos may be considered to be destabilizing if they protect population from a second strike. However, the paper assumes that PLU is achievable. If this assumption is rejected or significantly weakened, then the number of warheads per silo may be greater than a reasonable number of defending endos per silo. In this case it is necessary to consider use of exos.

ACKNOWLEDGEMENTS

Helpful suggestions have been made by Lowell Bruce Anderson, Thomas A. Brown, James E. Falk, Alexander H. Flax, Alan F. Karr, Glenn A. Kent, Wilbur B. Payne, Raymond E. Starsman, Bruce F. Stout, Victor A. Utgoff and John B. Walsh, to whom I am grateful.

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